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# Geo-environmental issues induced by the 2011 off the Pacific Coast of Tohoku Earthquake and tsunami

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**Abstract**

The 2011 off the Pacific Coast of Tohoku Earthquake of March 11, 2011, caused devastating geotechnical and geo-environmental issues mainly in the coastal area of the Tohoku and North-Kanto Regions, Japan. As a result of the earthquake and subsequent tsunami, approximately 23,000 Gg (23,000,000 t) of disaster debris was generated, with more than 12 million $m^3$ of tsunami deposits left in the flooded area. The geotechnical utilization of the soil fraction in the disaster debris and tsunami deposits has presented a huge challenge to geotechnical engineers since (1) the clearance of debris and tsunami deposits is an urgent task which must be completed within a few years and (2) although a large amount of waste-mixed soil can be used in the construction of new embankments and levees to protect the coast from future tsunamis, their geotechnical properties have temporal and spatial variations. This paper summarizes the current status on the generation, clearance, and treatment and utilization of disaster debris and tsunami deposits from geotechnical and geo-environmental viewpoints. In addition, the environmental monitoring data on soil and groundwater quality conducted over the affected area is briefly reviewed. The results of several wide-area monitoring efforts conducted by different organizations indicate that no significant soil or groundwater contamination has occurred. However, the localized contamination near industrial plants where toxic chemicals leaked due to the earthquake and tsunami needs to be carefully taken into consideration during future revival and redevelopment works. Another serious geo-environmental issue is the management of the radioactive contamination of surface soils caused by the accident at the Fukushima First Nuclear Power Plant. This paper summarizes the distributions and expected behaviours of radioactive Caesium in soils and groundwater, and outlines the possible remediation options for dealing with this contamination.


*Keywords:* The 2011 off the Pacific Coast of Tohoku Earthquake; Disaster debris; Tsunami deposits; Soil and groundwater quality; Geo-environmental contamination by accidental nuclides

## 1. Introduction

The 2011 off the Pacific Coast of Tohoku Earthquake, with a Richter magnitude scale of 9.0, occurred on March 11, 2011 off the Pacific Coast of the north-eastern part of the Honshu land, Japan leaving devastating damage in its wake in the Tohoku and Kanto Region. Due to this earthquake, a large scale tsunami hit the Pacific coast area of the Tohoku and Kanto Region including Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba Prefectures (Fig. 1).

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According to the Geospatial Information Authority of Japan, 561 $km^2$ was inundated by the tsunami; 24 $km^2$ in Aomori, 58 $km^2$ in Iwate, 327 $km^2$ in Miyagi, 112 $km^2$ in Fukushima, 23 $km^2$ in Ibaraki, and 17 $km^2$ in Chiba. This earthquake and subsequent tsunami resulted in a catastrophe, with massive loss of human life, and massive damage to buildings and infrastructures, as shown in Table 1. More than 90% of the deaths were due to drowning as a result of the tsunami, which also destroyed huge numbers of buildings and infrastructures on the coast. An enormous amount of disaster debris was generated as a result. In some tsunami-flooded areas, marine sediments were left onshore after the inundation phase, and are referred to as "tsunami deposits". The clearance, treatment, and utilization of disaster debris and tsunami deposits present an unprecedented challenge to geotechnical engineers and researchers.

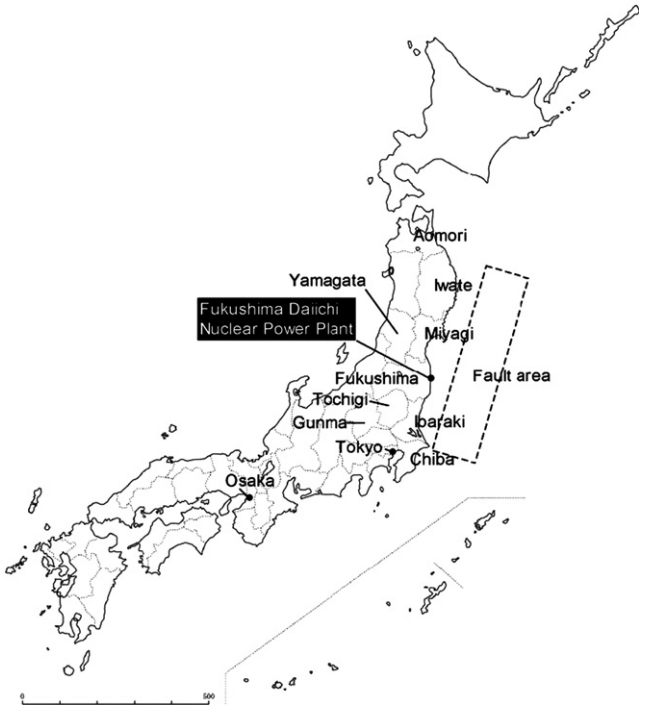


Fig. 1. Location of Prefectures of concern and Fukushima Daiichi Nuclear Power Plant.

In addition, the tsunami reached several of the nuclear power plants located along the Pacific coast line; Onagawa (Miyagi Prefecture), Fukushima Daiichi and Daini (Fukushima Prefecture), and Tokai Second (Ibaraki Prefecture) nuclear power plants. Among them, the Fukushima Daiichi nuclear power plant was seriously damaged by the 10 m plus tsunami that hit the coast there, and three reactors overheated due to severe damage to the emergency electricity supply system to cool the reactors. On March 14, 2011, hydrogen gas fuelled explosions occurred and large amounts of radioactive materials were spewed into the atmosphere. These radioactive materials were deposited by rain over the land surface in the Tohoku and Kanto Region. Radiation releases after deposition increased the ambient dose rate in the affected area, mainly in Fukushima, Tochigi and Gunma Prefectures (see Fig. 1), and caused large evacuations and concerns about the contamination of land, food and water resources.

Table 2 summarizes the geo-environmental issues caused by the 2011 off the Pacific Coast of Tohoku Earthquake and their features. Currently the focus is placed on six issues in particular: (1) disaster debris, (2) tsunami deposits, (3) soil and groundwater quality, (4) sanitary problems due to ground subsidence, (5) geo-environmental contamination caused by the accident at the Fukushima Daiichi nuclear power plant, and (6) conservation of water resources by use of the wells for disaster recovery. Among these issues, this paper briefly summarizes (1) current status on generation, clearance, treatment and geotechnical utilization of disaster debris and tsunami deposits, (2) the influences of the earthquake and subsequent tsunami on the geo-environment including the soil and groundwater in the affected area, and (3) the distribution and expected behaviour of the radioactive caesium emitted by the nuclear accident in the soils and groundwater, and possible remediation options for dealing with contamination.

## 2. Disaster debris and tsunami deposits

### 2.1. Generation and current status of disaster debris and tsunami deposit

Tables 3 and 4 summarize the generation of disaster debris (Aomori Prefecture, 2012; MOE (Ministry of the Environment, Japan), 2012a; Ibaraki Shinbun, 2012;

Table 1
Damage situation as of March 21, 2012 according to National Police Academy, Japan.

| Prefecture | Population | | Buildings | | | Infrastructures | |
|---|---|---|---|---|---|---|---|
| | Dead | Missing | Total-collapsed | Half-collapsed | Burned down | Road collapsed | Bridge damaged |
| Aomori | 3 | 1 | 311 | 852 | 0 | 2 | 0 |
| Iwate | 4755 | 1237 | 20,185 | 4562 | 15 | 30 | 4 |
| Miyagi | 9512 | 1688 | 84,749 | 147,165 | 135 | 390 | 29 |
| Fukushima | 1605 | 214 | 20,194 | 65,733 | 80 | 187 | 3 |
| Ibaraki | 24 | 1 | 2723 | 24,046 | 31 | 307 | 41 |
| Chiba | 20 | 2 | 798 | 9861 | 15 | 2343 | 0 |
| Other prefectures | 19 | 0 | 326 | 2413 | 5 | 659 | 1 |
| Total | 15,854 | 3143 | 129,286 | 254,632 | 281 | 3918 | 78 |

Chiba Nippou, 2012) and tsunami deposits (JSMCWM (Japan Society of Material Cycles and Waste Management), 2012) in the Prefectures that the tsunami hit on March 11, 2011; namely Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba Prefectures. The amount of tsunami deposits in each prefecture was roughly calculated based on the average deposit thickness measured at selected points (2.5–4.0 cm), the flooded area, and the assumed unit mass of each deposit (1.10 or $1.46 \times 10^3$ kg/m$^3$).

Based on the data summarized in Table 3, the total amount of debris created by the earthquake and subsequent tsunami exceeded 23,000 Gg, which is larger than the 20,000 Gg, generated by the 1995 Hyogoken-Nambu Earthquake (Hayashi and Katsumi, 1996). Fig. 2 shows the distribution of the debris generation in local governments located along the coastal line. Since most of the disaster debris was from the destruction caused by the tsunami as it hit buildings and structures located onshore, the debris discharge is distributed very widely along the shoreline. Inundation by seawater increased the salinity of the disaster debris in some affected areas, and this makes it difficult to incinerate it in incineration plants or in cement combustion furnaces. In addition, the debris was scattered by the tsunami and was left as a mixture of all different kinds of debris. Photo 1 shows the typical status of temporary storage of disaster debris at a stockyard in Iwate Prefecture. Disaster debris is composed of many types of materials: wood, paper, textiles, plastics, concrete, metal, tatami, soil, etc. In many stockyards, it was stored in a mixed state without any preliminary separation so that the clearance work could be completed as soon as possible. Fig. 3 shows the average composition of the disaster debris according to the statistics reported from Iwate and Miyagi Prefecture (Iwate Prefecture, 2011; Miyagi Prefecture, 2011). In these statistics, wood, plastics, and textiles are

Table 2
Geo-environmental issues caused by the 2011 Great East Japan earthquake and their features.

| Issues | Features |
|---|---|
| Disaster debris | > Generation of disaster debris of more than $23{,}630 \times 10^6$ kg<br>> Proper treatment and utilization of soil fraction<br>> Risk of contamination of stockyard due to the leachate generation |
| Tsunami deposit | > 13 to $28 \times 10^9$ kg of tsunami deposit in the flooded area<br>> Geotechnical utilization of tsunami deposit<br>> Contain salts and toxic chemicals |
| Soil and groundwater contamination | > Risk of soil and groundwater contamination due to the damage of storage facilities for toxic chemicals<br>> Tsunami-induced salinity damage to farmlands |
| Nuclear accident | > Distribution of nuclides in the environment, particularly in soil and groundwater<br>> Proper disposal of radioactive-contaminated waste |
| Sanitary and environmental issues | > Sanitary problems caused by continuous submerging (due to ground subsidence) |
| Wells for disaster recovery | > Utilization of wells at the affected area where water supply stopped<br>> Influence of the tsunami attack on the water quality |

Table 4
Estimation of tsunami deposit generation (JSMCWM, 2011).

| Prefecture | Flooded area (km$^2$) | Tsunami deposit in volume ($\times 10^6$ m$^3$) | Tsunami deposit in mass ($\times 10^6$ kg) |
|---|---|---|---|
| Aomori | 24 | 640–1020 | 700–1490 |
| Iwate | 58 | 2920–4680 | 3210–6830 |
| Miyagi | 327 | 5160–8260 | 5680–12,050 |
| Fukushima | 112 | 1570–2520 | 1730–3680 |
| Ibaraki | 23 | 1100–1760 | 1210–2570 |
| Chiba | 17 | 600–960 | 660–1400 |
| Total | 561 | 11,990–19,200 | 13,190–28,020 |

Table 3
Situation of debris generation and treatment.

| Prefecture | Debris generation in $\times 10^6$ kg | Storage in the stockyard in $\times 10^6$ kg (Ratio) | Treatment/disposal in $\times 10^6$ kg (Ratio) | As of | Source |
|---|---|---|---|---|---|
| Aomori | 202 | – | – | March 1, 2012 | Aomori Prefecture, 2012 |
| Iwate | 4755 | 4161 (88%)* | 478 (10.1%) | April 2, 2012 | MOE, 2012a |
| Miyagi | 15,691 | 11,395 (73%)* | 1184 (7.5%) | April 2, 2012 | MOE, 2012a |
| Fukushima | 2015 | 1380 (68%)* | 146 (7.3%) | April 2, 2012 | MOE, 2012a |
| Ibaraki | 755 | – | – | December 21, 2011 | Ibaraki Shinbun, 2012 |
| Chiba | 145 | – | – | January 31, 2012 | Chiba Nippou, 2012 |
| Total | 23,563 | – | – | – | – |

*Including the data for debris from demolition of damaged structures.

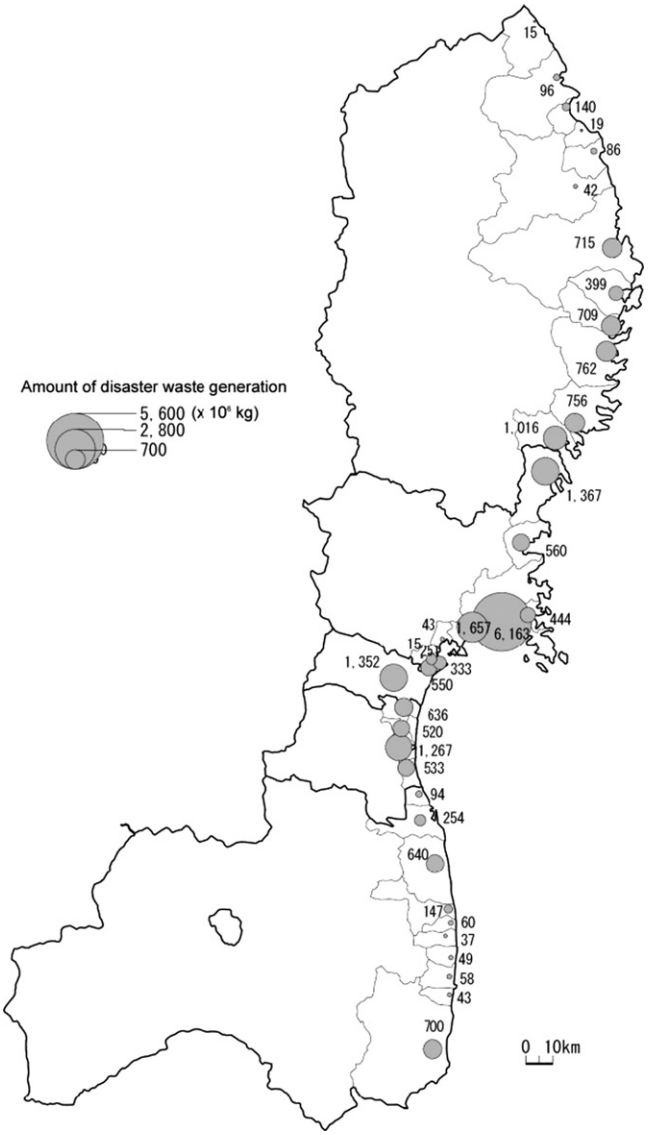


Fig. 2. Distribution of disaster waste generation in each local government (JGS, 2012).

classified as ''burnable (combustible) waste'', and concrete, soil, metal, and waste tatami are classified as ''unburnable wastes''. Although the degree of separation and classification applied to mixed debris may vary from site to site, about one third is burnable waste (Iwate: 35.7%, Miyagi: 29.6%) and two thirds is unburnable waste (Iwate: 62.4%, Miyagi: 70.6%). The ratio of burnable waste is much higher than that created by the 1995 Hyogoken-Nambu Earthquake, which was less than 20% (Hayashi and Katsumi, 1996). As of March 2012, most of the disaster debris has been stored in stockyards (Iwate: 100%, Miyagi: 99%), however, in Fukushima Prefecture, clearance work has not started yet in the area affected by the nuclear accident, and only two thirds of the total debris has been cleared so far. Furthermore, more debris is constantly being created by the demolition of buildings partially

Photo 1. Disaster debris placed in a stockyard in Iwate Prefecture (November 2011).

damaged by the earthquake and tsunami. For example, in Miyagi Prefecture, more than 50% of the debris is the result of demolitions (MOE, 2012a).

Photo 2 shows the status of the temporary storage of tsunami deposits at a stockyard in Iwate Prefecture. As of March 2012, almost all of the tsunami deposits have been cleared from urban and residential areas and stored in stockyards according to field surveys by the authors. However, most of the deposits in farmlands have not been cleared, as shown in Photo 3 (left). A typical cross section of the tsunami deposit in a flooded farmland is also shown in Photo 3 (right). During a certain period of inundation, finer particles were separated from denser and coarser particles and precipitated slowly upon a coarse layer that had been precipitated earlier than the finer particles. Accordingly, multiple layers with finer and coarser particles were formed upon the original ground. Fig. 4 shows the grain size distribution of finer and coarser layers collected at a farmland in the flooded area (Takai et al., 2012). The results indicated that the lower coarser layer is composed of sand only and has a much higher uniformity than the finer layer.

### 2.2. Characterization of tsunami deposits

Katsumi et al. (2011) investigated some physical properties of 17 tsunami deposit samples collected at five tsunami-affected sites (Sites I, S, N, Iw and W) in early April 2011 in Miyagi Prefecture. The water content of the tsunami deposits varied significantly, as shown in Photo 4. At some sites, such as Site H, the inundation had yet to completely subside due to poor drainage, which was caused by how the land was used or existing structures. Fig. 5 shows the grain size distribution of each sample collected (Katsumi et al., 2011), and Fig. 6 shows the fine fraction content ($<75\,\mu m$ in diameter) compared with the JGS classification for geo-materials according to JGS-0051 (JGS, 2009).

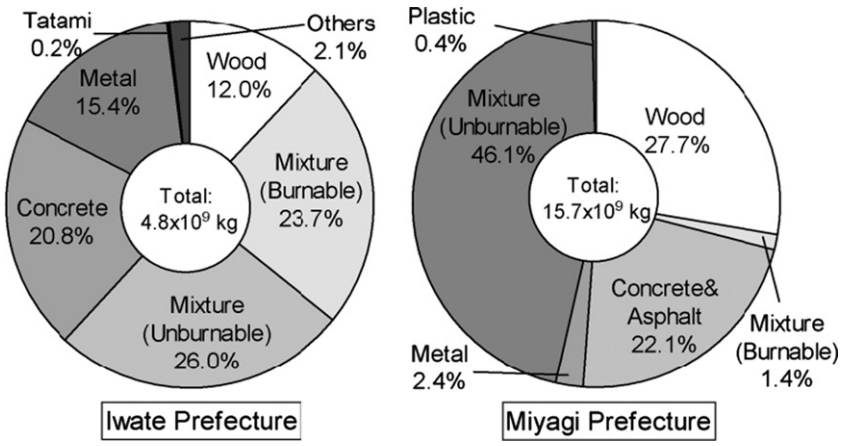


Fig. 3. Composition of disaster debris in Iwate and Miyagi Prefecture (Iwate Prefecture, 2011, Miyagi Prefecture, 2011).

Photo 2. Tsunami deposit placed in a stockyard in Iwate Prefecture (November 2011).

The maximum grain size of the samples of concern was limited to smaller than 2 mm, and accordingly, all the deposits can be classified into sand or fine-grained soil. More specifically, as mentioned in the previous section, the upper layers contains a higher fines fraction than the lower layers (sample S-2 and N-5). Another important finding is that the wet samples that were collected at the sites inundated for longer durations (S-1, H-1) contained a considerably larger fines fraction, particularly of particles finer than 10 μm (S-1: 20%, H-1: 32%). This is probably because the longer period of inundation enhanced the sedimentation of the fines fractions. Fig. 7 shows the relationship between the fines fraction content and ignition loss of the samples collected. Although some variation was observed from site to site, there is a mild linear correlation between these two factors. When the fine fraction content is smaller than 20%, the ignition loss is expected to be below 5%. MLIT (Ministry of Land, Infrastructure, Transports and Tourism, Japan) is promoting the utilization of tsunami deposits as well as soil fraction in mixed disaster debris (1) to construct parks and green spaces as a redundancy zone against a huge tsunami (MLIT, 2012a) and (2) fill embankments in areas where significant ground subsidence due to the earthquake occurred (MLIT, 2012b). Thus, determining the engineering properties of the tsunami deposits is important to ensure the stability of these earthen structures; ignition loss is an important factor, since it can be used as an index of the potential of long-term settlement.

### 2.3. *Issues in the management of disaster debris and tsunami deposits*

Katsumi et al. (2012) investigated the Proctor compaction properties of waste-mixed soil samples collected at temporary stockyards for mixed disaster waste and tsunami deposits, and at a treatment facility of disaster debris. The focus was placed on the influence of the content of the combustible fraction on compaction properties. The results clearly indicated that the existence of combustible matter like wood and textiles influenced compactibility, and that a higher content of combustible fraction resulted in a lower maximum dry density. The need for efficient separation and treatment processes to extract waste matters selectively from waste-mixed soil and tsunami deposits is, therefore, quite clear. Figs. 8 and 9 show the typical flow for the treatment of mixed debris, according to the master plan for the treatment of disaster waste (MOE, 2011a), and tsunami deposits, according to the guideline from MOE (2011b). The fundamental concept of this plan and guideline is that as much reusable material, such as concrete debris, wood waste, and electric appliances, should be extracted from the mixed debris and treated properly, and the amount of landfill and associated cost should be minimized. In a practical treatment process, large fractions, such as concrete, timber, and metal, are first separated manually or mechanically for reusing/recycling. Afterwards, through crushing and sieving processes, waste matter is selectively removed from mixed waste, and then incinerated and/or disposed of in waste landfills, as shown in Fig. 8. However, the fraction finer than the minimum opening size of the

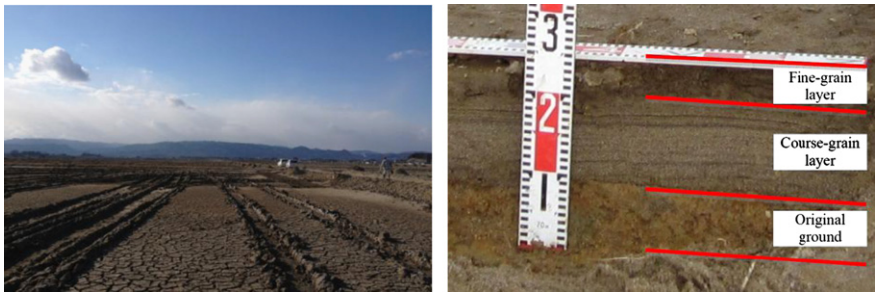


Photo 3. Tsunami deposit in farmland: An overall view (left) and a layered cross section of tsunami deposit (right).

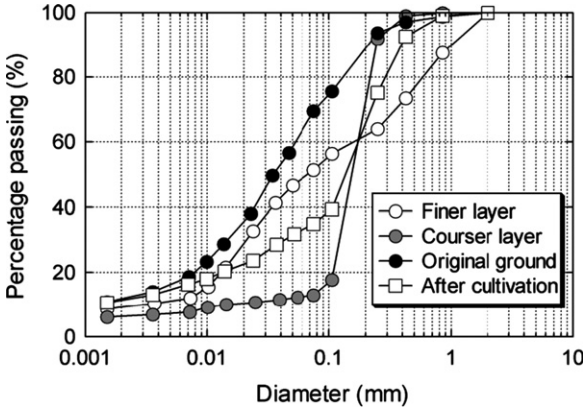


Fig. 4. Grain size distributions of tsunami deposits separated during the sedimentation (Takai et al., 2012).

sieve employed in the treatment remains as a residue after treatment. This residual fraction is a soil-based material containing a certain amount of small waste pieces such as wood chips. Photo 5 shows the appearances of six different waste-mixed soil samples collected at several temporary storage yards and treatment plants. The waste content varied significantly depending on the sampling site and the treatment process to which the samples were subjected. From a geotechnical viewpoint, it is important to determine whether the content of residual waste matter in the soil is acceptable, according to applications and the engineering performance required. In field observations done by the authors, small wood chips remain in the soil even after repeated sieving, and this wood fraction has an adverse effect on the compactibility of the soil. One of the solutions to improve the compactibility is a grain size control by a combined use of soil and waste concrete aggregates, which can be easily produced by crushing and sieving demolished concrete debris at stockyards.

From an environmental viewpoint, the emission of asbestos, which was also revealed after the 1995 Hyogoken-Nambu Earthquake (Cabinet Office, Government of Japan, 2006), should be carefully considered during the clearance of disaster debris and the demolition of damaged structures. The results of air monitoring by MOE (2011c) indicated that although the concentration of asbestos in the public environment in Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba Prefectures, including temporary stockyards for disaster debris and the tsunami affected area were similar to usual values, the concentrations close to ventilation openings for asbestos removal works were remarkably high, at more than 10 fibre/L. According to Terazono et al. (2012), large amounts of broken asbestos boards were identified and placed in a mixed state with other demolition debris at temporary stockyards, although spray-on asbestos seemed less problematic. Therefore, in the transportation and treatment process of disaster debris afterwards, the emission of asbestos should be continuously monitored and the working environment needs to be kept safe.

## 3. Soil and groundwater quality

### 3.1. Concentrations of toxic substances in soil and groundwater

Immediately after the earthquake, soil and groundwater contamination by the leakage of toxic chemicals from damaged industrial facilities was a matter of concern. One reason for this concern is that after the Hyogoken-Nambu Earthquake on January 17, 1995, the groundwater was contaminated by tetrachloroethylene (PCE) leakages from some laundry facilities (Cabinet Office, Government of Japan, 2006). Thus, MOE as well as some research groups have conducted a wide-area monitoring for soil and groundwater quality in the affected area. (MOE, 2011d, e, f, g, h and b; Iizuka et al., 2012). Tables 5 and 6 summarizes briefly the results of wide-area monitoring for soil and groundwater quality conducted by MOE. Iizuka et al. (2012) investigated the leaching concentrations of toxic substances in more than 10 surface soil samples collected in the flooded zone; namely Ishinomaki and Sendai, Miyagi Prefecture. Fig. 10 shows an example of the leaching test results, with arsenic concentrations shown for the ten different samples (Iizuka et al., 2012). In addition, the leaching concentrations of toxic substances were examined in tsunami deposits (Katsumi et al., 2011; MOE, 2011i; Tsuchiya et al., 2012). Table 7 shows the chemical properties of tsunami deposits collected on early April 2011 in the flooded area, Miyagi Prefecture (Katsumi et al., 2011). The main observations drawn from these previous surveys are described in the following paragraphs.

Photo 4. Overviews of the sampling sites (Left: Site S, Right Site H) (Katsumi et al., 2011).

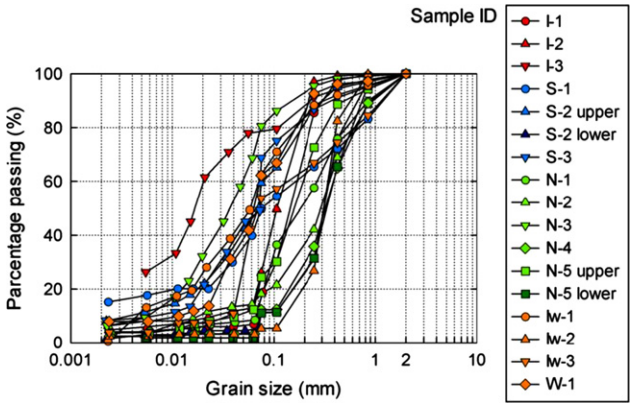


Fig. 5. Grain size distributions of tsunami deposits collected on early April (Katsumi et al., 2011).

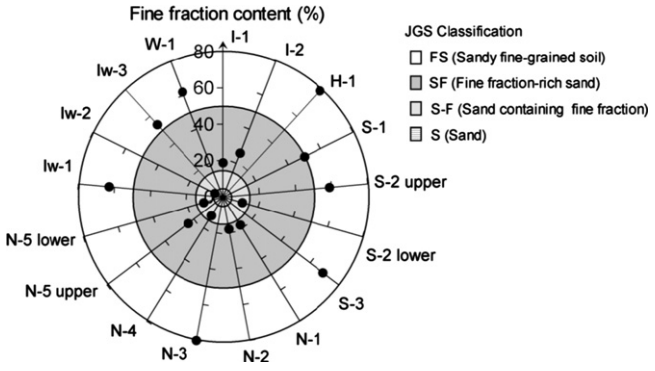


Fig. 6. Fine fraction contents of the tsunami deposits in conjunction with JGS classification of geo-materials (based on Katsumi et al., 2011).

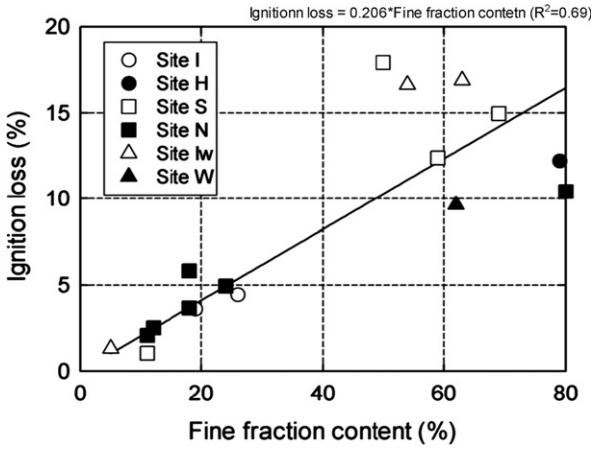


Fig. 7. Relationship between the fine fraction content and ignition loss of tsunami deposits (based on Katsumi et al., 2011).

No organic chloride compounds were detected with concentrations higher than the environmental criteria for soil and groundwater quality even in the tsunami deposits. This supports the claim that no widespread contamination occurred due to the earthquake and tsunami. However, in very limited spots, high concentrations of lead, n-hexane extracts and TPH (total petroleum hydrocarbon), which are an index of oil contamination, and PCB were detected, although there is no definite evidence that the earthquake and tsunami triggered these contaminations. Oguchi et al. (2012) characterized the chemical composition of tsunami deposits in conjunction with location of facilities dealing with toxic chemicals, and indicated that all tsunami deposit samples containing high level of hazardous chemicals were collected near the facilities where the particular detected chemicals were stored and/or used. Since the monitoring carried out by the MOE and some other research groups was not conducted inside areas owned by the private sector and was limited to publicly owned land, their surveys were unable to detect localized surface soil contamination in industrial facilities. Based on field observations by the authors several weeks after the earthquake, there were some smells which had come from the leakage of chemicals in the tsunami-affected area. Therefore, in the future, environmental risk caused by localized soil contamination in industrial facilities should be carefully considered prior to reconstruction works. Another important finding is that surface soil contamination by dioxins was caused by the open burning of disaster waste (MOE, 2011i).

Concerning the tsunami deposit, leaching concentrations of lead, serene, boron, fluoride, and/or arsenic higher than the environmental criteria were observed at some sampling points. However there was no proof that the earthquake and tsunami caused these leaching. The observed leaching concentrations were slightly higher than the criteria and similar to the background concentrations at the site of


Fig. 8. Typical flow chart for the treatment of mixed debris.

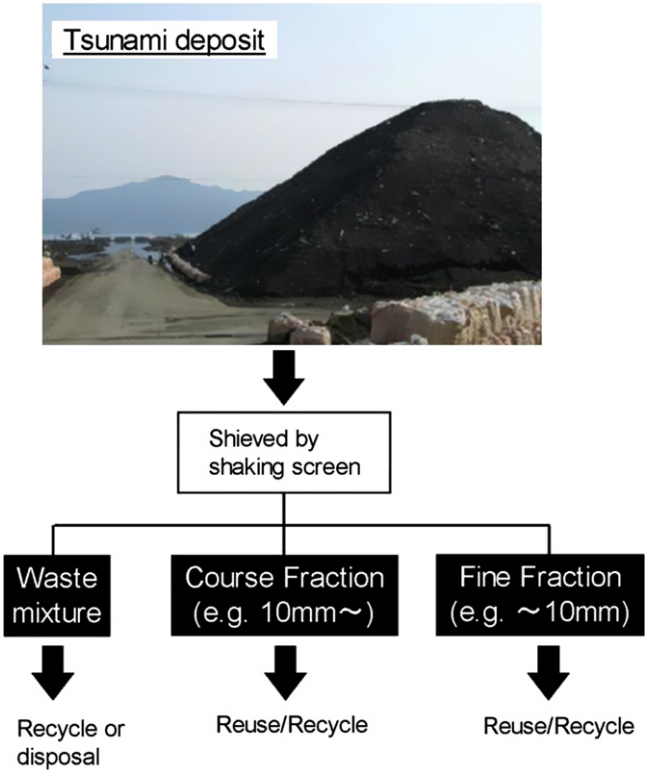


Fig. 9. Typical flow chart for the treatment of tsunami deposit.

concern in many cases. According to the MLIT (2010), the concentrations of boron and fluoride in the marine sediment in the Tohoku Region were considerably higher than those in other regions in Japan. In the flooded area, continuous inundation after the tsunami may have resulted in increased concentrations of boron and fluoride since the seawater itself contains certain concentrations of both (boron: about 4.5 mg/L, fluoride: about 1.5 mg/L), which are higher than the environmental criteria (boron:1.0 mg/L, fluoride: 0.8 mg/L). Tsuchiya et al. (2012) pointed out that the tsunami deposit samples with higher leaching concentrations for several heavy metals (Cu, Pb, As, etc.) were collected around mouths of the rivers, along the upper stream of which mining were executed. Based on the discussions above, it is reasonable to conclude that, in many cases, the leaching of these inorganic elements was caused by elements which exist naturally in the soil and sediments. In the geotechnical utilization of tsunami deposits containing unacceptable levels of natural-derived toxic substances, these deposits should not be transported to different sites, but used on-site with cost-effective methods used to control the migration of toxic substances, such as using a capping to reduce infiltration.

### 3.2. *Salinity of soil and groundwater in the flooded zone*

From the view point of salinity, soil with a salinity of higher than 1 mg/g or an electrical conductivity (EC) of higher than 1–2 mS/cm is not suitable for use as a basement layer or for planting, since the corrosion of foundation structures embedded in the soil has to be considered. Thus, prior to utilizing the tsunami deposits as geo-materials, their chemical properties including salinity, EC and pH needs to be assessed if the construction of foundation structures is also planned.

The area of farmland flooded by the tsunami was approximately 236,000 ha. Particularly, in the coast zone of South Iwate, Miyagi and North Fukushima, more than 30% of the farmland was flooded. Fig. 11 shows the histogram of salinity for tsunami deposit samples in a flooded farmland in Fukushima (Takai et al., 2012). Salinity higher than 2 mg/g was detected so frequently that desalination works were clearly necessary for planting.

The salinity of groundwater in the flooded area is an important issue, since wells are expected to act as water resources for domestic and agricultural purposes if the water supply is stopped due to earthquake or tsunami. In fact, water supply was stopped in 2.3 million residential houses due to the 2011 off the Pacific Coast of Tohoku Earthquake, and a lot of wells were utilized by residents living in the affected area. As explained in the previous section, no groundwater contamination by toxic substances has been caused by the earthquake and tsunami. However, according to the results of some field surveys (Kaihotsu et al., 2011; Mori et al., 2012; Sugita, 2012), EC values and/or salinity in the shallow unconfined aquifers increased by a factor of 10 at maximum due to seawater intrusion. In many cases, the seawater entered the shallow aquifers by infiltrating vertically through the ground surface during the inundation. However, Sugita (2012) pointed out

Photo 5. Overviews of the waste-mixed soil samples from several sites.

Table 5
Brief summary of soil quality monitoring by MOE (2012b).

| Prefecture | No. of monitoring points | No. of points where concentrations exceed the criteria | Chemicals of concern (No. of points) |
|---|---|---|---|
| Aomori | 16 | 3 | Leaching: Mercury (1), Lead (3), Arsenic (1), Fluoride (2)<br>Content: Lead (1) |
| Iwate | 34 | 5 | Leaching: Fluoride (5) |
| Miyagi | 72 | 30 | Leaching: Lead (16), Arsenic (25) |
| Fukushima | 31 | 6 | Leaching: Lead (2), Arsenic (3), Fluoride (1)<br>Content: Lead (1) |
| Ibaraki | 11 | 0 | – |
| Chiba | 11 | 3 | Leaching: Lead (3) |
| Total | 175 | 47 | – |

Table 6
Brief summary of groundwater quality monitoring by MOE (2011d to 2011 g).

| Prefecture | No. of monitoring points | No. of points where concentrations exceed the criteria | | Chemicals of concern | |
|---|---|---|---|---|---|
| | | June–July, 2011 | October 2011 | June–July, 2011 | October 2011 |
| Aomori | 11 | 0 | – | – | – |
| Iwate | 29 | 0 | – | – | – |
| Miyagi | 28 | 1 | 0 | Lead | – |
| Fukushima | 111 | 5 | 3 | Lead, Arsenic, Nitrate nitrogen, Fluoride, PCE | Nitrate nitrogen |
| Ibaraki | 36 | 0 | – | – | – |
| Total | 215 | 6 | 3 | – | – |

the possibility that the seawater was flowing downward directly along the wells. Even after several months, the groundwater quality had not fully recovered. Although groundwater quality naturally recovers in the long term, the recovery is expected to be delayed. First of all, tsunami deposits containing salt still remain on the ground surface, and the recharged water therefore contains a certain concentration of salt. Mori et al. (2012) pointed out the effects of irrigation in the Sendai Plain; irrigation is an important source of groundwater recharging in the Sendai Plain, however, the amount of recharge from irrigation water was significantly decreased since planting was cancelled in many farmlands due to the severe damage incurred due to the disaster. Considering the situation, the salinity in the groundwater should be carefully monitored in the future, particularly for agricultural use.

## 4. Radioactive contamination of soils

### *4.1. Outline of the Fukushima Daiichi nuclear power plant accident*

After the earthquake, the subsequent tsunami with waves of more than 10 m hit the Fukushima Daiichi

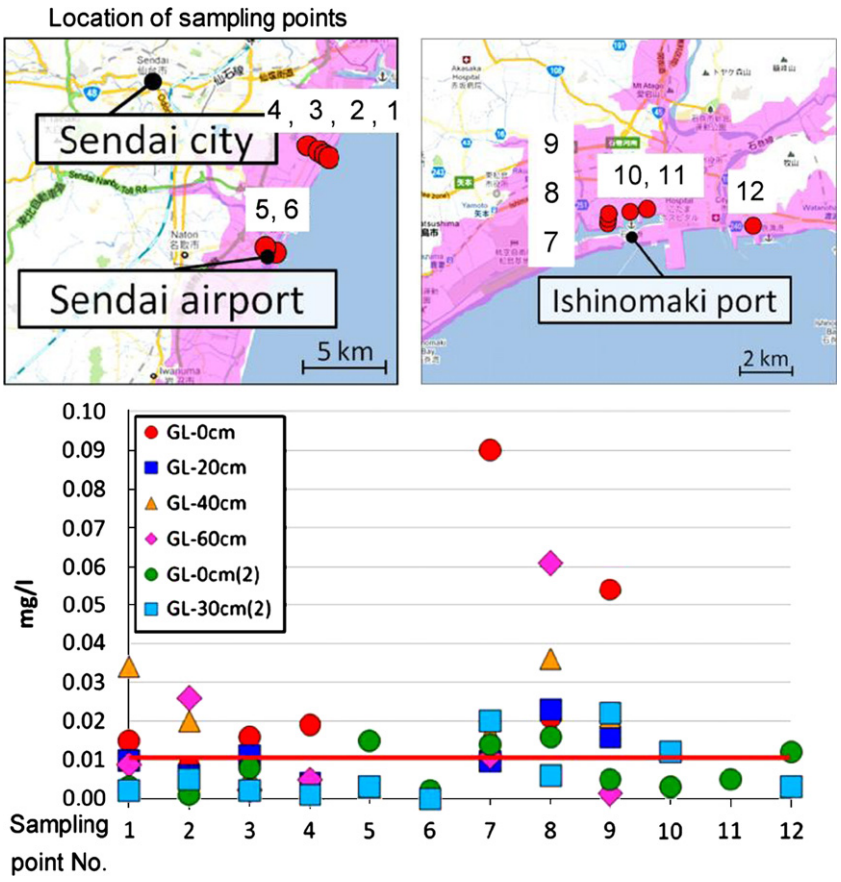


Fig. 10. An example of leaching test results for soil samples in the flooded area: Leaching concentrations of arsenic (Iizuka et al., submitted for publication).

Table 7
Example of chemical properties of tsunami deposits (Katsumi et al., 2011).

| Sample ID* | Solid density (Mg/m$^3$) | Ignition loss (%) | pH | EC (S/m)** | Eh (mV) | Salinity (%) | Leaching concentration*** | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Fluoride (mg/L) | Arsenic (mg/L) |
| I-1 | 2.743 | 3.62 | 8.16 | 0.638 | 146 | 0.34 | – | – |
| I-2 | 2.693 | 4.46 | 7.89 | 0.782 | −111 | 0.40 | 0.5 | 0.016 |
| H-1 | 2.638 | 12.23 | 7.21 | 1.600 | −50 | 0.91 | 0.2 | 0.004 |
| S-1 | 2.712 | 17.94 | 7.00 | 1.859 | −65 | 1.07 | 0.5 | 0.002 |
| S-2 upper | 2.595 | 12.39 | 8.32 | 0.106 | 134 | 0.05 | 0.2 | 0.002 |
| S-2 lower | 2.708 | 1.05 | 8.24 | 0.016 | 150 | 0.00 | 0.4 | – |
| S-3 | 2.541 | 14.97 | 6.70 | 1.018 | 178 | 0.55 | N.D. | – |
| N-1 | 2.886 | 3.67 | – | – | – | – | – | – |
| N-2 | 2.724 | 5.82 | – | – | – | – | – | – |
| N-3 | 2.629 | 10.43 | – | – | – | – | 1.3 | 0.019 |
| N-4 | 2.781 | 2.52 | – | – | – | – | 0.2 | N.D. |
| N-5 upper | 2.838 | 4.95 | – | – | – | – | 0.5 | 0.004 |
| N-5 lower | 2.660 | 2.08 | – | – | – | – | 0.2 | – |
| Iw-1 | 2.625 | 16.90 | – | – | – | – | – | – |
| Iw-2 | 2.791 | 1.32 | – | – | – | – | N.D. | N.D. |
| Iw-3 | 2.743 | 16.65 | – | – | – | – | 0.4 | N.D. |
| W-1 | 2.801 | 9.65 | – | – | – | – | – | – |

*The meaning of Sample ID: "Capital letter (Index of sampling location)-Number (sample No. in each location)".
**EC: Electrical conductivity.
***N.D.: Not detected; Underlined values are higher than environmental criteria in Japan.

Nuclear Power Plant, which is located in the Futaba District of Fukushima Prefecture, around 15:30, March 11, 2011. There are six reactors (Nos. 1–6) at the Plant, three of which (Nos. 1, 2 and 3) were under operation at the time of the earthquake. Although they shut down automatically at the moment the earthquake occurred, the

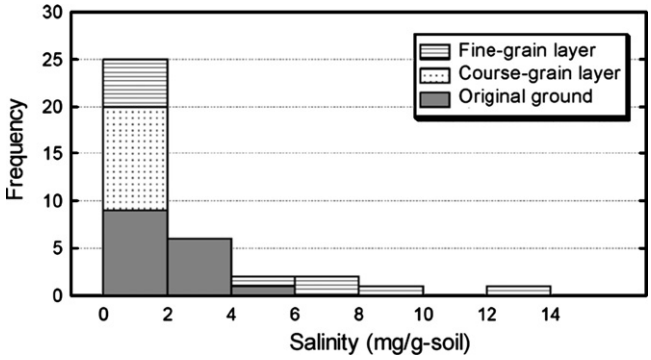


Fig. 11. Histogram on the salinity of the tsunami deposits collected at farmlands in Fukushima Prefecture (Takai et al., 2012).

Photo 6. Abandoned farmland in the planned evacuation zone.

emergency electricity supply system to cool the reactors was badly damaged afterwards, and the reactors began to overheat and eventually went out of control. On March 14, 2011, hydrogen gas fuelled explosions occurred in both the Nos.1 and 3 reactors. They spewed large amounts of radioactive materials including $^{131}I$, $^{134}Cs$, and $^{137}Cs$ into the atmosphere, reaching levels 10–15% of the estimated emissions at Chernobyl on April 26, 1986, according to the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. (MEXT, 2012).

These radioactive materials were deposited by rain over the land surface, particularly on the surface soil in Tohoku and North Kanto Regions. Radiation releases after deposition increased the ambient dose rate in the affected area and, accordingly, caused large evacuations and concern about food and water supplies. As of March 2012, neither the no-entry zone nor the planned evacuation zone had been abolished. Also in the no-entry zone and the planned evacuation zone, rice planting is prohibited (Photo 6) due to soil contamination. In this section, the distribution and behaviour of radioactive materials in the contaminated soil is outlined, and various countermeasure methods are considered, with the issues associated with them described in detail.

### *4.2. Distribution of radioactive chemicals in soils and groundwater*

The radioactive materials released into the atmosphere were carried by wind and fell on the sea and land surface by rain and snow. The amount of radioactive caesium-137 ($^{137}Cs$) and iodine-131 ($^{131}I$) deposited over the land estimated by a chemical transport model was about 22% and 13% of the total release, respectively, and the rest was deposited over the ocean or out of the model domain (Morino et al., 2011). A large part of the radioactive materials deposited on the land has decayed naturally, however, the rest remains on/in the soil, roads, existing structures, forests, etc.. From the wide-area monitoring using aircraft (MEXT, 2011a) as of November 2011, the highly contaminated areas, where the amount of $^{134}Cs$ and $^{137}Cs$ deposited on the land surface exceeds 3 million Bq/m$^2$, are distributed north-westward from the plant (the red coloured area in Fig. 12). Regions in which the deposition exceeds 60,000 Bq/m$^2$ are not only central areas of Fukushima prefecture but also several parts of Tochigi, Gunma, and Ibaragi prefectures, more than 200 km away from the plant, depending on the weather conditions immediately after the explosions. According to a survey by the Ministry of Agriculture, Forestry and Fisheries

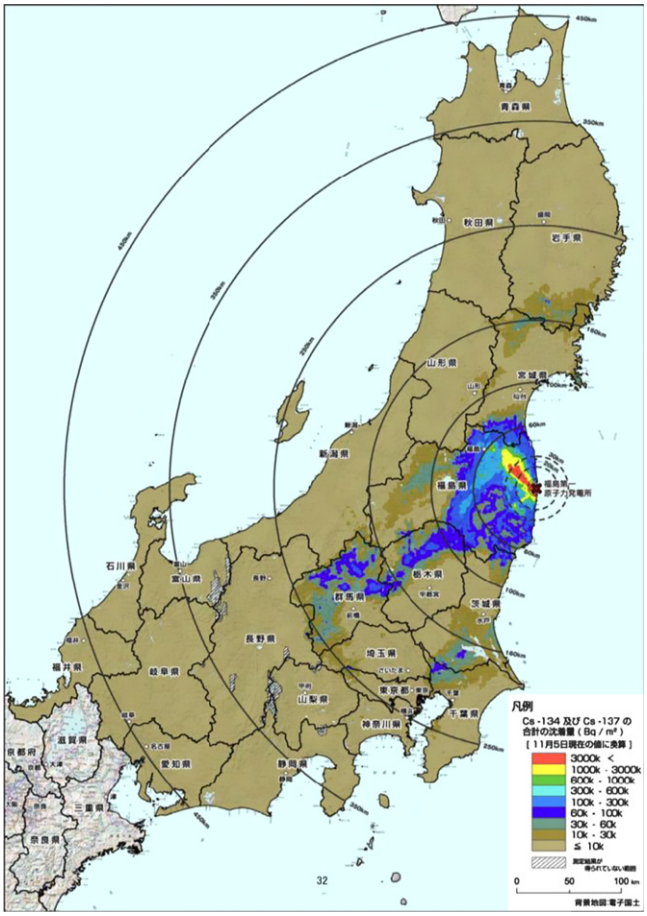


Fig. 12. Amounts of $^{134}Cs$ and $^{137}Cs$ deposition estimated by aircraft monitoring (MEXT, 2011a).

(MAFF) (MAFF, 2012), an area of about 8,300 ha of agricultural land has concentrations of radioactive materials in the surface soils (0 to −15 cm below the surface) of over 5,000 Bq/kg. Also, the Ministry of Environment (MOE) estimated the volume of contaminated soil in areas where the ambient dose rate of radioactive rays exceeds 5 mSv/yr to be 20,833,000–28,385,000 $m^3$ (MOE, 2011j). The concentrations of $^{134}$Cs and $^{137}$Cs correlate very well with each other with the abundance ratio of $^{134}$Cs to $^{137}$Cs at 0.92 (MEXT, 2012), which means both $^{134}$Cs and $^{137}$Cs have behaved in a similar manner in the environment.

The MOE also monitored the concentrations of radioactive materials in the groundwater at more than 270 points in Fukushima Prefecture as well as about 40 points in all the adjacent prefectures (Miyagi, Yamagata, Ibaraki, Tochigi) (MOE, 2011k). As of November 2011, no radioactive material ($^{131}$I, $^{134}$Cs or $^{137}$Cs) was detected except for 1 Bq/L radioactive caesium detected at two points located in the no-entry zone (within 20 km distance from the plant). This fact suggests that the mobility of radioactive material in the soil is very limited.

### 4.3. Behaviours of radioactive chemicals in soils and groundwater

The concentrations of radioactive materials deposited on the soil decreases as a result of (1) reduction due to spontaneous decay, (2) infiltration into the soil, (3) outflow by surface runoff, and (4) absorption by terrestrial plants. Reductions in concentration from spontaneous decay are governed by the half-life of the individual radioactive materials. Temporal changes in the concentrations of radioactive elements in the soil in Iitate village measured by MEXT are shown in Fig. 13 (MEXT, 2011b). The concentration of $^{131}$I (half-life of about 8 days) decreased to less than 100 Bq/kg in mid June despite hundreds of thousands Bq/kg in March. Conversely, concentrations of the two radioactive materials with long half-lives, $^{134}$Cs (half-life about two years), and $^{137}$Cs (half-life about 30 years) decreased slightly by November 2011. Thus, the target radionuclides in the remediation phase are mainly $^{134}$Cs and $^{137}$Cs.

An important environmental fate of radioactive caesium in the soil is its well-known very low mobility due to the strong sorption in clay minerals. One reason for this is that the negative charges on the surface of clay particles in soil readily adsorb radioactive caesium, which exists as a positive ion in soil. Another reason is that the edges of certain kinds of clay minerals, such as illite, can strongly adsorb hydrated radioactive caesium (Ishikawa et al., 2007). An example of survey results on the longitudinal gradient of radioactive caesium concentrations in soils is shown in Fig. 14 (Yasutaka et al., 2011a). Although the survey was conducted about four months after the accident, the results indicate that more than 80% of the radioactive caesium remains in the surface 1 cm layer of the soil. Other survey results also confirmed that more than 90% of the radio caesium remained in the top surface (~5 cm) if the surface soil was not disturbed (MAFF, 2012; Shiozawa et al., 2011).

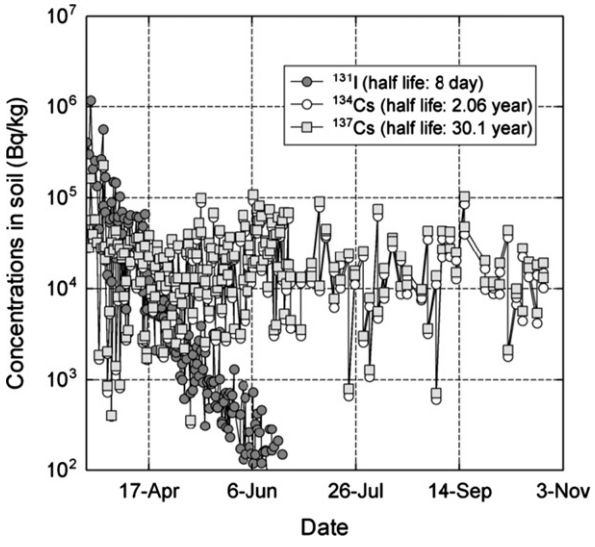


Fig. 13. Variation in the concentrations of radioactive elements in the soil with time at Yagisawa in Iitate village, Fukushima Prefecture (MEXT, 2011b).

### 4.4. Countermeasure Methods and related Issues

Methods to reduce the human health risks from radioactive Cs in contaminated soil, which comes mainly from

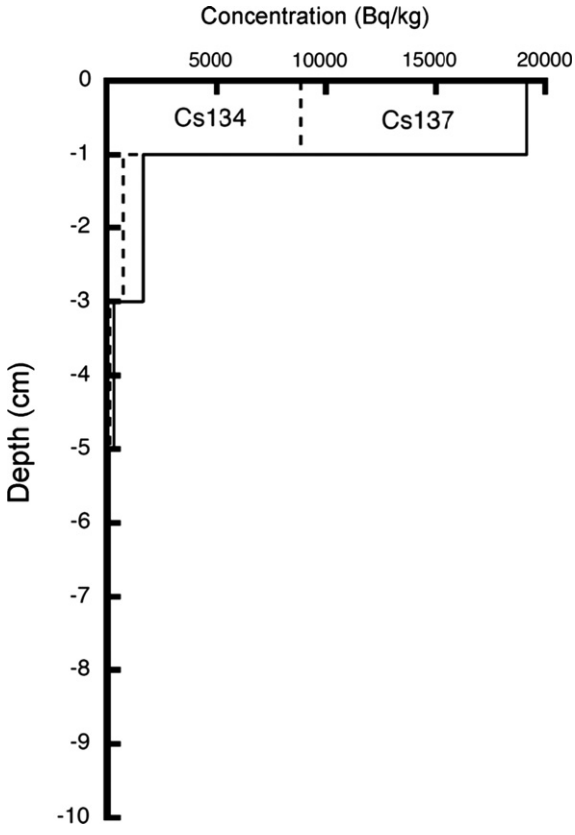


Fig. 14. Distribution of $^{134}$Cs and $^{137}$Cs concentrations with increasing soil depth in Koriyama City, Fukushima Prefecture on July 24, 2011 (Yasutaka et al., 2011a).

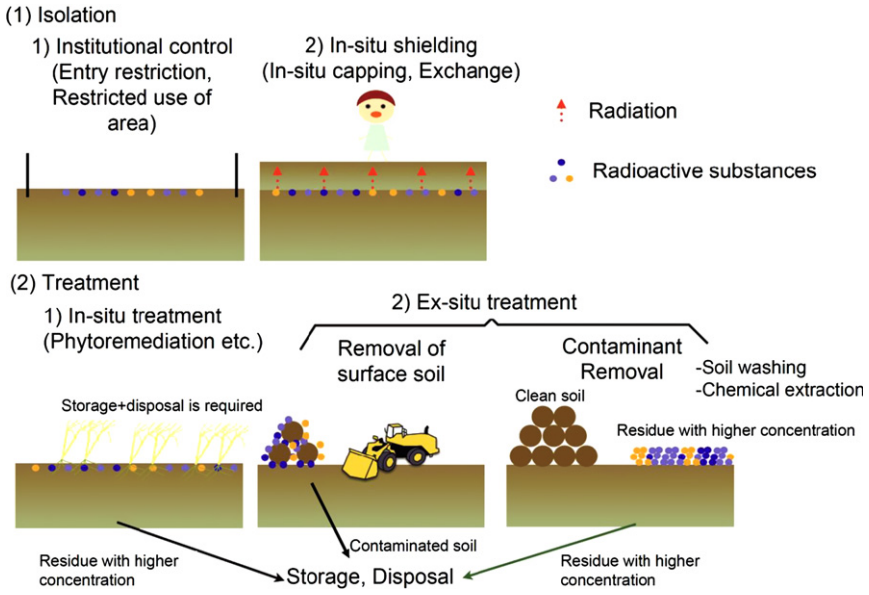


Fig. 15. Methods to reduce human health risks from radioactive Cs in contaminated soil (Yasutaka et al., 2011c).

external exposure (Yasutaka et al., 2011b), can be roughly classified into two categories, isolation and treatment, as shown in Fig. 15. The purpose of isolation is to reduce external exposure by leaving the contaminated soil in situ without decontamination. Possible options to isolate contaminated soils include (1) institutional control such as entry restriction, restricting the use of areas to keep a distance between receptors and the contaminated soil, and (2) in situ containment such as constructing a capping layer and turning the soil to attenuate the radiation from the contaminated soil. Treatment intends to actively reduce the concentration of radioactive Cs in the soil. Possible treatment options include the following in situ decontamination techniques: phytoremediation and ex situ treatment methods, such as soil washing, chemical extraction, and the removal and subsequent storage of surface soil. In the next sections, the authors briefly describe the remediation technologies by the removal of surface soil including ex-situ volume reduction technologies. Further information about the big picture of technologies or individual technologies for remediation of radioactive Cs contaminated soil, is made available by the IAEA (1999) in English or Yasutaka et al. (2011c) in Japanese.

Remediation by the removal of surface soil is composed of three phases; (1) the removal of surface soil from the site, (2) volume reduction, and (3) storage and management, as shown in Fig. 16. The radioactivity of radioactive materials decreases only by spontaneous collapse of the radioactive material itself. Therefore, even if contaminated soil is removed from the sites, it is necessary to store and manage it until the amount of radiation decreases to a safe level. Simultaneously, it is necessary to reduce the volume of soil contaminated with radioactive Cs since enormous volumes of surface soil are expected to be removed. There are two major volume reduction techniques available; soil washing and

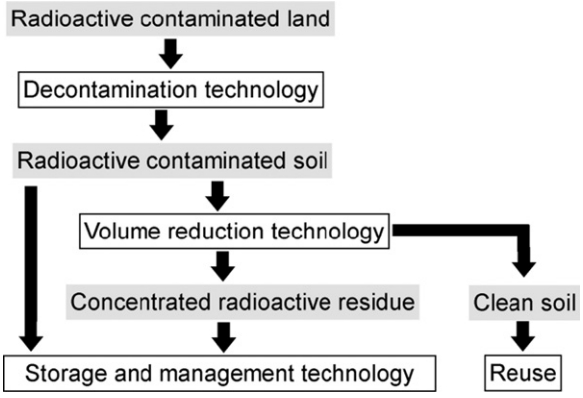


Fig. 16. Conceptual remediation flows by the removal of contaminated surface soil.

chemical extraction. Soil-washing is a typical method in the remediation of soil contaminated with heavy metals. The method is designed to remove radioactive caesium by washing with water and classification processing, which is more applicable to sandy soils than to clayey soils. The example of soil-washing test results for two sandy soil shown in Table 8 (Yasutaka et al., 2011a) indicate that about 70–90% of the radioactive caesium is removable from sandy soils. The chemical extraction is a method of extracting radioactive Cs from contaminated soil using acids, such as nitric or sulphuric acid, under high temperature conditions. The feature of this method is that it can remove the radioactive caesium which is not removable by soil-washing only. However, it is currently at the stage of laboratory or verification testing, and future progress is expected. In selecting a suitable volume reduction technology, it is necessary for the concentrations in the contaminated soil, the type of soil, and the target decontamination level for clean fraction to be taken into consideration.

Table 8
Results of laboratory soil washing test for sandy soils (Yasutaka et al., 2011a).

| Soil type | Sandy soil A | Sandy soil B |
|---|---|---|
| Concentration of $^{134}Cs+^{137}Cs$ in contaminated soil (Bq/kg) | 13,500 | 7700 |
| Concentration of $^{134}Cs+^{137}Cs$ after soil washing (Bq/kg) | 1500 | 1837 |
| Decontamination ratio (%) | 89 | 76 |

It should also be noted that a higher concentration of waste is produced when more effective volume reduction technology is employed.

## 5. Concluding remarks

This paper summarizes the representative geo-environmental issues caused by the 2011 off the Pacific Coast of Tohoku Earthquake and the subsequent huge tsunami; namely (1) generation of disaster debris and tsunami deposits in the tsunami-affected area, (2) soil and groundwater quality influenced by the earthquake and tsunami, and (3) geo-environmental contamination by radioactive materials caused by the accident in Fukushima Daiichi nuclear power plant. In reconstruction projects, tsunami deposits as well as mixed disaster debris after treatment are expected to be utilized as embankments or filling materials in coastal areas where ground subsidence occurred or in the green zone behind the seawalls as a tsunami-redundancy zone. The geotechnical properties of waste mixed soil have spatial and temporal variations, and have not been fully studied. In particular, dynamic stability and long-term settlement are of main concern in utilizing these materials. However, previous research on the geo-technical properties of waste landfills, and probabilistic stability analysis approaches etc. are able to contribute a lot to utilizing the waste-mixed soil more reliably. With regard to the geo-environmental contamination by accidental nuclides, a huge amount of contaminated soil and waste materials is expected to be discharged in the near future. The MOE (2011l) already has some guidelines on the treatment of waste contaminated by accidental nuclides in place. The guidelines are intended to make use of the hydraulic barrier performance of compacted clayey soils and the capacity of clay minerals to absorb radioactive materials to ensure they are effectively contained inside stockyards and disposal facilities.

Considering these situations, engineers and researchers in the geo-environmental engineering field can play several important roles in reconstruction projects to ensure the safety of earthen structures with waste mixed soil and containment facilities for waste materials contaminated with accidental nuclides.

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